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A MODEL REFERENCE BASED SLIDING MODE APPROACH FOR PARAMETER-VARYING SYSTEMS

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ABSTRACT

This paper presents a Model Reference-based Sliding Mode Control in order to deal with the control of parameter varying systems. The examined system is a Permanent Magnet DC-drive, which is nominally a linear, time-invariant first order system. By dependence of the parameters of the states it turns into a linear, time-variant system of first order. Sliding-Mode Control (SMC) is known for certain robustness properties, which comes along with the drawback of high switching amplitudes and switching frequency. Model Reference Adaptive Systems (*MRAS*) are used to adapt control parameters to unknown dynamics via Lyapunov-stability criteria.

The SMC consists of a continuous part and a discontinuous part. While the continuous part is a feedforward control, the discontinuous part is a pure switching control. The adaptation scheme works as a load observer, so it can not distinguish between an external load or the change of a parameter. So the feedforward and switching control are both adapted to load changes and parameter variations. The switching amplitude may be weighted by the error between reference and measurement as well as by the adapted parameters.

Index Terms— MRAS, DC-Drive, Sliding Mode Control, Adjusting gain

1. INTRODUCTION

In the following paper the development of an Adaptive Sliding Mode Controller, that consists of a continuous and a discontinuous part is presented. While the discontinuous part is a Sliding-Mode Controller with adjusting amplitude, the continuous part is a feedforward control based on a Modell Reference Adaptive System. Sliding Mode Control (*SMC*) comes along with robustness of the closed loop against unmodeled dynamics and unknown loads as well as drawbacks like high loads and electro-mechanical stress of involved actors due to the high switching characteristics of SMC. Aim of the introduced scheme is to reduce the switching of the controller while keeping the benefits of the SMC.

To examine the effects and limitations of the proposed scheme regarding the quality of control and the maximum order of the open loop, a speed control of a DC-drive is implemented by the Model Reference-Based Sliding Mode Control (*MRSMC*). The controlled DC-drive is a nonlinear, parameter varying first order system. The MRAS is used to adopt the static gain of the DC-drive, so the self-adjusting gain of the discontinuous part is used to achieve robustness against disturbances and in this manner a zero steady state error as well.

The following paper is organized as the following. After this brief introduction the second section presents the structure of the chosen controller, including an introduction to SMC as well as to MRAS. The third section shows the chosen controller structure and the results of simulations of the closed loop for two kinds of reference-signals. The paper is closing with a conclusion of the results.

This paper is meant as a contribution to a discussion regarding the use of Adaptive Sliding Mode techniques and is therefore providing the basic ideas and information about both techniques and some results based on simulations. Based on this results of the simulations conclusions are drawn regarding advantages and drawbacks of the proposed scheme. Since severe drawbacks come along with this scheme, this paper does not present the end of the evolution of speed control, it provides an idea and experiences made with this combination of techniques.

2. STRUCTURE OF THE CONTROLLER

The following section will present the structure of the chosen controller as well as a brief introduction to both used techniques of SMC and MRAS.

The proposed scheme is shown in figure 1.

The control signal u is the sum of the discontinuous signal $u_{dc}(t)$, which is generated by the Sliding-Mode Control block "'SMC"', and the continuous signal u_f, which is result of the feedforward control-block "'FF"'. While the only input to the SMC-block is the error $e(t) = u_r(t) - x_p(t)$ between the plant output $x_p(t)$ and the reference signal $u_r(t)$, the feedforward control is fed by the reference $u_r(t)$ and the adapted gain $\hat{k}(t)$.

The controller is given by the system of equations

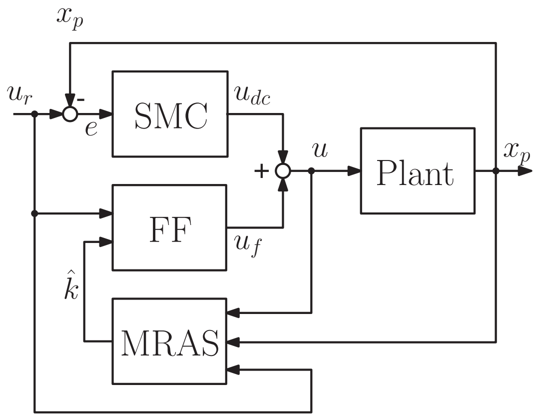


Fig. 1. Structure of a Model Reference Based Sliding Mode Controller

2 to 4:

$$u(t) = u_{dc}(t) + u_f(t) \tag{1}$$

$$u_{dc}(t) = \begin{cases} +\Gamma(\Delta) & \text{if} \quad (\mathrm{s}\dot{\mathrm{s}}) < 0 \\ -\Gamma(\Delta) & \text{if} \quad (\mathrm{s}\dot{\mathrm{s}}) > 0 \end{cases} \tag{2}$$

$$u_f(t) = \hat{k}^{-1}(t) u_r(t) \tag{3}$$

$$\hat{k}(t) = f_{MR}(e(t), u_r(t), x_p(t)) \tag{4}$$

$\Gamma(\Delta)$ is the self-adjusting switching gain of the discontinuous SMC, that is a function of a metric distance Δ. The switching condition is computed by the switching function s and its first derivative with respect to time $\dot{s}$. The adapted gain $\hat{k}$ is determined as a function of the state error $e(t)$, the reference signal $u_r(t)$ and the state x_p. The case $(\mathrm{s}\dot{\mathrm{s}}) = 0$ needs to be covered in implementations by a third state or by choosing $\leq / \geq$ instead of $< / >$.

In order to explain the function of the given controller system, both techniques of SMC and MRAS are going to be introduced in the both following subsections.

2.1. Sliding Mode Control

Sliding Mode Control is well known discontinuous control technique, which is examined since the 1940s [1] and which got more and more importance since the 1970 due to essentially Russian developments [2]. Especially the use of SMC for electrical drives has been examined very well, no matter if it's about induction motors [3], stepper motors [4], Synchronous Motors [5] or DC-drives [6],[7].

Since the theory is well documented (i.e. [8],[9]), this paper will just present the basic idea of SMC and the resulting error-based switching function of the SMC, regarding the second order phaseplane.

The main properties of the SMC shall be discussed regarding the following linear time-invariant system in state-space notation:

$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}u + \mathbf{D}f_D \tag{5}$$

where $\mathbf{x} \in R^n$ is the space vector and $\mathbf{D} \in R^{(n \times l)}$ the input-matrix of the disturbance function $f_D \in R^l$. u is the scalar input-signal. f_D represents all factors affecting the performance of the closed loop. The main idea is to force the state vector onto a $(n-m)$-dimensional subspace, where m is the number of input-signals. On this subspace the system is then dominated by some special dynamics, which is shown in the following.

The design-procedure consists mainly of two parts:

1. Define a state-dependant switching-function
$$\mathrm{s}(\mathbf{x}) = \mathrm{S}\mathbf{x},\ \mathrm{S} \in R^{m \times n}$$
2. Consider a controller with switching characteristic as given. Then ensure by choosing both the switching criteria and the switching gain that the state-vector reaches the subspace s and is kept on it.

Lets assume a certain S and a corresponding controller-law u

$$u = \begin{cases} +u_0 & \text{if} \quad (\mathrm{s}\dot{\mathrm{s}}) < 0 \\ -u_0 & \text{if} \quad (\mathrm{s}\dot{\mathrm{s}}) > 0 \end{cases} \tag{6}$$

be given, that $\mathrm{s} = \mathbf{0}$ holds. The condition $\mathrm{s} = \mathbf{0}$ is reason for some special properties, which are shown now. If $\mathrm{s} = \mathbf{0}$ holds, the order of the closed-loop is *reduced* by m. The system may always be transformed into (e.g. [8, 10]):

$$\begin{aligned} \dot{\mathbf{x}}_1 &= \mathbf{A}_{11}\mathbf{x}_1 + \mathbf{A}_{12}\mathbf{x}_1 \\ \dot{\mathbf{x}}_2 &= \mathbf{A}_{21}\mathbf{x}_1 + \mathbf{A}_{22}\mathbf{x}_2 + \mathbf{B}_2\mathbf{u} + \mathbf{D}\mathbf{f}_S \end{aligned} \tag{7}$$

with $\mathbf{x}_1 \in R^{n-m}$ und $\mathbf{x}_2 \in R^m$. The switching function s follows as:

$$\mathrm{s} = \mathbf{C}_s\mathbf{x}_1 + \mathbf{x}_2 \tag{8}$$

If $\mathrm{s} = \mathbf{0}$ holds, the order of the system is reduced to $(n-m)$ due to eqn. (9):

$$\mathbf{x}_2 = -\mathbf{C}_s\mathbf{x}_1 \Rightarrow \dot{\mathbf{x}}_1 = \big(\mathbf{A}_{11} - \mathbf{A}_{12}\mathbf{C}_s\big)\mathbf{x}_2 \tag{9}$$

The even more important property is the *invariance* versus unmodeled dynamics and disturbances. As seen in eqn. (9), the closed loop does not depend on the disturbance f_D any more. If disturbances and unmodeled dynamics act in the range of $\mathbf{B}$, the influence of disturbances and unmodeled dynamics onto the system is canceled. This *matching*-conditions can be expressed as [11]:

$$f_D \in range(B) \tag{10}$$

To ensure, that the state vector reaches the Sliding-manifold S, the *reaching-conditions* must hold:

$$\mathcal{V}(\mathbf{x},t) = \mathrm{s}^T\mathrm{s}, \quad \text{and} \quad \dot{\mathcal{V}} < \kappa < 0, \quad \kappa \in R \tag{11}$$

$\mathcal{V}(\mathbf{x},t)$ is therein a Lyapunovfunction along the trajectories of the closed loop. If eqn. (11) holds, the equilibrium $\mathrm{s} = \mathbf{0}$ is asymptotically stable. Another condition is

$$\mathrm{s}\dot{\mathrm{s}} < 0 \tag{12}$$

which is equivalent to [12]:

$$\lim_{\mathrm{s}\mapsto -0} \dot{\mathrm{s}} > 0 \quad \text{and} \quad \lim_{s\mapsto +0} \dot{\mathrm{s}} < 0 \tag{13}$$

which ensures that the trajectory of the closed loop is always oriented towards the switching manifold.

Due to the switching characteristics and the corresponding discontinuity the differential equations at $\mathrm{s} = \mathbf{0}$ is not defined. To describe the motion of $\mathbf{x}(t)$ on the Sliding manifold, the technique of the *equivalent control* is used. The equivalent control is the virtual, continuous control law $u_{eq}(t)$, that would bound the state vector on the sliding manifold as well as the discontinuous one. $u_{eq}(t)$ is computed for $\dot{\mathrm{s}} = \mathrm{s} = 0$ as the following (assuming: $det\,(\mathrm{S}\mathbf{B}) \neq 0$):

$$\begin{aligned} \dot{\mathrm{s}} &= \mathrm{S}\dot{\mathbf{x}} = \mathrm{S}\left(\mathbf{A}\mathbf{x} + \mathbf{B}u_{eq} + \mathbf{D}f_D\right) = 0 \\ \Rightarrow u_{eq}(t) &= -(\mathrm{S}\mathbf{B})^{-1}\left(\mathbf{D}f_D + \mathbf{A}\mathbf{x}\right) \end{aligned} \tag{14}$$

With the equivalent control law the system dynamics in the Sliding Mode may be expressed as [13]:

$$\dot{\mathbf{x}} = \left[\mathbf{I} - \mathbf{B}\left(\mathbf{C}\mathbf{B}\right)^{-1}\mathbf{C}\right]\mathbf{A}\mathbf{x} = \mathbf{A}_{eq}\mathbf{x} \tag{15}$$

By choosing the matrix S properly, the poles of $\mathbf{A}_{eq}$, which determine the dynamics during the Sliding Mode can be placed, and therefore the whole theory of linear state-space-control may be used to design the sliding manifold.

To illustrate some of the named properties, the SMC of the following linear, unstable second order system is shown:

$$\ddot{x}(t) = u(t) + d\dot{x}(t) + cx(t),\ d > 0,\ c > 0 \tag{16}$$

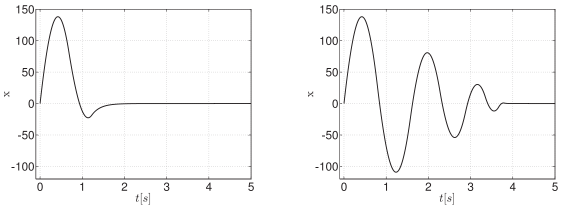
Assume a switching controller:

$$u(t) = \begin{cases} +u_0 & \text{if} \quad (\mathrm{s}\dot{\mathrm{s}}) < 0 \\ -u_0 & \text{if} \quad (\mathrm{s}\dot{\mathrm{s}}) > 0 \end{cases} \tag{17}$$

with the corresponding switching function s:

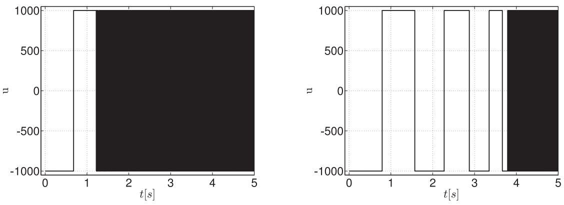
$$\mathrm{s} = \lambda x + \dot{x},\ \lambda > 0 \tag{18}$$

Let $\|u_0\|$ be the input-signal corresponding to the maximum actor power. So the only parameter free to choose is therefore $\lambda > 0$. λ has to be chosen in the awareness of the trade-off between fast reaching of the Sliding Mode and fast dynamics during the Sliding Mode. During the Sliding Mode $\dot{x} = -\lambda x$ holds. The larger λ is chosen, the longer it takes the trajectories to reach the Sliding Mode, as it is indicated by the time-plots fig. 2 of the state $x(t)$ and the input-signal $u(t)$: Although the dynamics during the Sliding Mode gets faster, for $\lambda = 20$ it takes a longer time for the system to reach the origin of the phase-plane due to the longer reaching-phase. Two further things are to be noticed:



(a) $\lambda = 5$ (b) $\lambda = 20$

Fig. 2. State $x(t)$ for two different λ



(a) $\lambda = 5$ (b) $\lambda = 20$

Fig. 3. Input-signal $u(t)$ for two different λ

1. During the Sliding Mode high frequent switching action takes place, which is undesired because of the electro-mechanical stress and higher losses.

2. It is possible to stabilize two instable systems by combining them via a special switching function.

Sliding Mode is for the named reason an interesting control technique due to its advantages, while the drawbacks require some augmentation of the controller law of eqn. (2).

2.2. Feedforward-Control involving MRAS

As mentioned before, the augmentation of a SMC with a feedforward-control makes sense in order to reduce the necessary switching gain Γ. The implemented feedforward $u_f(t)$ control is a very simple one, which incorporates only the static gain $\hat{k}$ of the plant:

$$u_f(t) = \hat{k}^{-1}(t)u_r(t) \tag{19}$$

For the control of a parameter-varying System it might be useful to adopt this gain. This might be done using the *Modell-Reference Adaptive Systems* (MRAS), which is going to be introduced in the following section.

Consider the given nonlinear first order system:

$$\dot{x}_p(t) = a_p x(t) + k_1 u(t) + k_2 g(u) \tag{20}$$

where a_p, k_1 and k_2 are unknown parameters of the systems. The estimator may have the form [14]:

$$\begin{aligned}\hat{x}_p(t) =& a_m \hat{x}_p(t) + (\hat{a}_p(t) - a_m)\, x_p(t) + \\ & \hat{k}_1(t) + \hat{k}_2 g(u)\end{aligned} \tag{21}$$

where $\hat{x}_p$ is the estimated state, a_m a tuning parameter, and $\hat{a}_p(t), \hat{k}_1(t), \hat{k}_2$ are the adapted parameters. So the error $e(t)$ between the real plant state $x_p(t)$ and the estimated one is:

$$e(t) = \hat{x}_p(t) - x_p(t) \tag{22}$$

Computing the first derivative of $e(t)$ with respect to time yields:

$$\begin{aligned}\dot{e}(t) =& a_m e(t) + (a_p(t) - a_p)\, x_p(t) \\ &+ \left(\hat{k}_1(t) - k_1\right) u(t) + \left(\hat{k}_2(t) - k_2\right) g(u)\end{aligned} \tag{23}$$

Defining

$$\phi(t) = \hat{a}(t) - a,\ \psi = \hat{k}_1(t) - k_1,\ \Lambda = \hat{k}_2(t) - k_2 \tag{24}$$

one can set up a Lyapunovfunction $\mathcal{V}$ to determine the adaption laws for the unknown parameters:

$$\mathcal{V} = \frac{1}{2}\left(e^2 + \phi^2 + \psi^2 + \Lambda^2\right) \tag{25}$$

Computing the first derivative including eqn. (23) with respect to time yields:

$$\begin{aligned}\dot{\mathcal{V}} =& a_m e(t) + \phi\left(e(t)x_p(t) + \dot{\phi}(t)\right) \\ &+ \psi\left(e(t)u(t) + \dot{\psi}(t)\right) + \Lambda\left(e(t)g(u) + \dot{\Lambda}(t)\right)\end{aligned} \tag{26}$$

$\mathcal{V} > 0$ is guaranteed by its quadratic form. Choosing $a_m < 0$ and canceling all terms including $\phi(t), \psi(t)$ and $\Lambda(t)$ one achieves $\dot{\mathcal{V}} < 0$ and therefore the origin is uniformly stable in the large [14]. Canceling the named terms yields:

$$\begin{aligned}\dot{\phi}(t) &= \dot{a}_p(t) = -e(t)x_p(t) \\ \dot{\psi}(t) &= \dot{k}_1(t) = -e(t)u(t) \\ \dot{\Lambda}(t) &= \dot{k}_2(t) = -e(t)g(u)\end{aligned} \tag{27}$$

To ensure the convergence of $\hat{a}_p(t)$, $\hat{k}_1(t)$ and $\hat{k}_2(t)$ to their real values, a persistent excitation is needed [14].

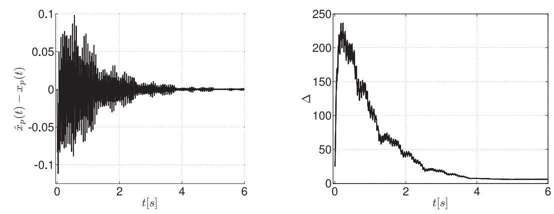
Let the plant be a permanent magnet DC-Drive, that may be described by a first order nonlinear system, with an input dependent gain $f(u)$:

$$T_{DC}\dot{\omega}(t) = f(u)u(t) - \omega(t) \tag{28}$$

where T_{DC} is the characteristic time-constant and $f(u)$ is the input-dependent gain:

$$f(u) = A + Be^u \tag{29}$$

The parameter-identification corresponding to the described method has been carried out for an input-signal $u(t) = \sum_{i=1}^{n} \sin(2\pi f_i i)$. The output error $e(t) = \hat{x}_p(t) - x_p(t)$ and the norm $\|\Delta\| = \sqrt{\psi^2(t) + \Lambda^2(t)}$ of the parameter-errors are shown in the following figures:



(a) Output-error e(t) (b) Norm of the parameter-error

Fig. 4. Error-signals of the carried-out simulation

As it is shown in fig. 4 (a)/(b), the output error tends to zero oscillating around the the zero-line, while the parameter does not tend to zero. Determining "good" parameters and initial values for the identification is difficult. The parameter -identification can to be modified regarding the improvement of the convergence of the parameter-error.

The modified parameter-identification is shown in the context of the Model Reference Based Sliding Mode Approach in the following section.

3. MODEL-REFERENCE ADAPTIVE BASED SLIDING MODE APPROACH

In order to reach a better convergence-speed of the parameter -identification, the adaption-scheme is changed to a "In-The-Loop" identification. The modified feed-forward input-signal $u_f(t)$ is:

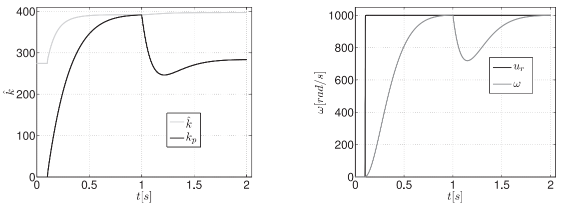
$$u_f(t) = \hat{k}(t)u_r(t) \tag{30}$$

where $\hat{k}(t)$ is the adopted gain and $u_r(t)$ the reference signal. The gain $\hat{k}(t)$ is computed as:

$$\begin{aligned}\hat{k}(t) &= \hat{k}_1(t)\hat{k}_0 u_r(t) - \hat{K}_2(t)u_r(t) \\ \dot{k}_1(t) &= \gamma_1\left(u_r(t)e(t)\hat{k}_0 u_r(t)\right) \\ \dot{k}_2(t) &= \gamma_2\left(-u_r^2(t)e(t)\right)\end{aligned} \tag{31}$$

where $\hat{k}_0$ is the initial guess of the gain k, and $\gamma_{1,2}$ are adaption parameters free to chose. This closed-loop scheme will lead to a zero-steady state error. By adapting $\hat{k}(t)$ such, that $\omega(t) \mapsto u_r(t)$ holds, the real gain $k(t) = \hat{k}^{-1}$ is computed. Choosing the adaptive law in this way, the adaption got a mixture between a pure MRAS-identification and a MRAS-controller, since its neither delivering the gain k nor computing the input-signal, but its adapting the gain in the closed loop via $u_f(t)$.

Carrying out the closed-loop simulation for a step $u_r = 1000rad/s$ and a disturbance at $t = 1s$ yields the following time-plots. As it is shown in fig. 5, the



(a) Adapted gain $\hat{k}(t)$ (b) DC-speed $\omega(t)$

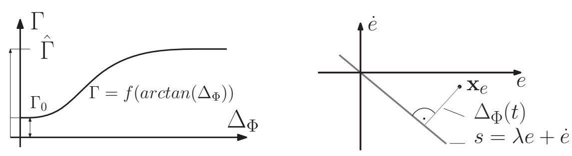
Fig. 5. Closed loop step responses

adopted gain $\hat{k}$ tends to the "true" value k. The reaction to the disturbance at $t = 2s$ is a steady-state deviation that maps the disturbance to a change in the gain, which might be interpreted as an increase of a resistance.

The closed loop according to eqn. (2) is augmented with a SMC with adjusting gain:

$$u_{dc}(t) = \begin{cases} +\Gamma(\Delta_\Phi) & \text{if} \quad (\mathrm{s}\dot{\mathrm{s}}) < 0 \\ -\Gamma(\Delta_\Phi) & \text{if} \quad (\mathrm{s}\dot{\mathrm{s}}) > 0 \end{cases} \tag{32}$$

where the switching gain Γ is a function of the metric distance of the error vector $\mathbf{x}_e = (\dot{e}/e)$ to the switching function s as shown in fig. 6:



(a) Gain $\Gamma(\Delta_\Phi)$ (b) Metric distance Δ_Φ

Fig. 6. Computation of Γ

The error e is $e(t) = u_r(t) - \omega(t)$ and the switching function is defined as: $\mathrm{s} = \lambda e + \dot{e}$.

Two simulations for the proposed scheme are carried out. The first simulation is the closed-loop step-response to $u_r = 1000rad/s$ and a disturbance at $t = ss$ The second simulation is the closed-loop response to a siniusoidal input signal. The corresponding speed and input-signals are donated in the time-plots as ω_1 and u_1.

Both closed-loop performances are compared to a SMC with adjustable gain according to fig. 6 and a feedforward control with constant gain:

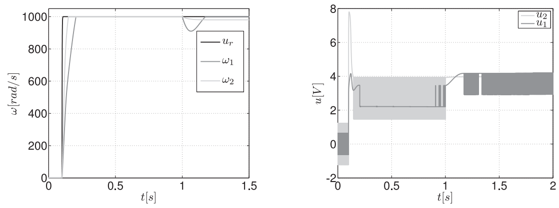
$$u_f(t) = \overline{k}^{-1} u_r(t) \tag{33}$$

where $\overline{k}$ ist the mean-value of the range of upper bound k_{max} and lower bound k_{min} of the "real" gain k:

$$\overline{k} = \frac{k_{max} + k_{min}}{2}$$

The corresponding speed and input-signals are donated in the time-plots as ω_2 and u_2.

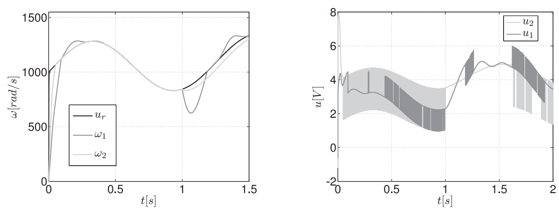
Carrying out the first simulation for both controller schemes yields the time-plots for the corresponding ω_1 and ω_2: As seen in fig. 7, ω_1 and ω_2 reach the reference-



(a) Speeds $\omega_1(t)$ and $\omega_2(t)$ (b) Input-signals $u_1(t)$ and $u_2(t)$

Fig. 7. Closed-loop step-response

signal quick without overshooting, the dynamic of ω_2 is a bit higher than the one of ω_1. The adaptive SMC compensates the disturbance, while the non-adaptive SMC does not and the corresponding closed-loop response keeps a steady-state error. The switching of the input signal u_1 and u_2 are as expected reduced with respect to a "pure" SMC, the mean-value of the input-signal is increased, so the electro-mechanical stress is reduced. The closed loop responses ω_1 and ω_2 to a siniusoidal



(a) Speeds $\omega_1(t)$ and $\omega_2(t)$ (b) Input-signals $u_1(t)$ and $u_2(t)$

Fig. 8. Closed-loop siniusoidal-response

input signal are displayed in fig. 8 (a). Without disturbance influence both schemes provide a zero steady-state error. The non-adaptive SMC can not compensate the disturbance, therefore a non-zero steady-state error remains, while the adaptive SMC can compensate the disturbance. The input-signals $u_1(t)$ and $u_2(t)$ do not vary significantly.

The proposed Adaptive Sliding-Mode scheme works well for step-responses. For fast changing input-signals the quality of the adaptive scheme is limited. Both described schemes provide a reduction of the switching action while giving a good dynamics due to the use of the full actor power, which is included in the controller-law according to eqn. (3).

4. CONCLUSION

This paper presents an combination of Adaptive Control and Sliding Mode Control with selfadjusting gain. After explaining the motivation for choosing the proposed scheme in section 1 the structure of the adaptive SMC is shown in section 2 both combined controller-techniques are introduced in the subsections 2.1 and 2.2. Simulated closed-loop-responses including the adaptive SMC-scheme and a non-adaptive SMC scheme are compared in section 3.

The result of the proposed adaptive scheme depends strongly on the variation of the input-signals, due to the slow-adaption-speed. For step-responses the adaptive scheme provides good-dynamics and robustness vs. the uncertain gain. The switching gain could be reduced compared to the non-adaptive scheme, the mean-value of the input-signals was up-leveled and therefore the mechanical stress and losses reduced.

A real drawback of the use of MRAS-techniques is the adoption of the included parameters, which has to be done manually. Furthermore the parameters have to be changed for every kind of input-signal.

So there is some work to be done left. At first the proof of stability has to be carried out for the proposed scheme, regardless the simulation results. Next work to be done is to determine the parameters as a function of the input-signals.

Although the combination of the two robust-control techniques Sliding-Mode Control and Model-Reference Adaptive Systems is promising and gives some good results, the drawbacks are not to be neglected and for sure need some improvement.

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